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Final Report for High Precision Short-Pulse Laser Ablation System for Medical Applications

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Final report for

High Precision Short-Pulse Laser Ablation System for Medical Applications

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SUMMARY

During the three year LDRD funding period, we studied the ablation characteristics of biological tissues using ultrashort pulse lasers (USPL) with pulse widths varying from 100 femtoseconds to tens of picoseconds. During the first year, we performed extensive theoretical studies to develop an improved understanding of the USPL ablation process. Two optical signals were tested for feasibility of use in real-time feedback systems during high repetition rate ablation. In the second year, we devised a real-time, feedback-controlled USPL ablation system, based on luminescence, which may be useful for sensitive micro-spinal surgeries. Effective laser parameters were identified to reduce collateral damage. The final year of the project focused on quantification of the pressure pulse induced by USPL ablation of water surfaces representing biological tissues. Results of these studies were presented in invited talks at domestic and international conferences and numerous journal articles were published (see bibliography). This effort has increased our scientific understanding of physical processes important for the therapeutic biomedical application of ultrashort pulse lasers, and has taken the first steps toward practical realization of such applications.

Year 1

Commercially available ultrashort laser pulses (USLP) are intense enough to cause optical breakdown and plasma formation (hot ionized vapor) via direct multiphoton absorption in insulators. Since the nonlinear absorption is an order of magnitude higher than the linear absorption due to chromophores, most of the pulse energy is concentrated in a thin surface region (100 – 200 nm). The high energy density accumulation in a thin superficial layer results in high local pressure (~ 1 Mbar) and temperature (~ few eV) which are quickly released by rapid plasma expansion and shockwaves [1,2,3,4]. Due to this fast ejection of the plasma, the energy transfer to the lattice of the material is minimized leaving virtually no collateral damage to the surrounding area. That is, the shockwave has high initial pressure which rapidly disperses which propagation into the material. One dimensional modeling studies revealed that the peak pressure during the pulse can be as large as 1 Mbar and the corresponding temperature rise can reach up to 20 eV (1eV = 11600 °K) with input laser energy fluence of 1.5 J/cm^2 and 500 fs pulse duration. The high pressure reduces to several kbar after penetrating only tens of microns. Compared to ablation caused by nanosecond pulses, significant temperature rise is limited to the near surface area.

Experiments showed that the ablation rate in dentin is approximately 1 μm/pulse which corresponds to removal of 1 mm/sec using a 1 kHz repetition rate system. Scanning electron microscopy (SEM) studies verified lack of collateral damage at the ablation craters [5,6,7,8].

Year 2

Knowing that short pulse lasers can effectively remove material while leaving minimal collateral damage, we devised a feedback controlled ablation system to eliminate possible damage to adjacent sensitive tissues. During the first year, preliminary work focused on discrimination between calcium based hard tissues and carbon based soft tissues using either fluorescence or plasma luminescence [9]. This feedback technique is targeted for application to micro-spinal surgery in which there is a need to remove bone tissue without harming nerve tissues. Our studies showed that luminescence spectroscopy is superior for discrimination of bone and nerve tissues. A computer-controlled feedback system utilized the high intensity luminescence of calcium at 616 nm and it was used in selective ablation of the bone tissues successfully [10].

Ablation thresholds were measured for hard dental tissues (dentin) and water and it was found that the threshold increases at longer pulse widths [6,11]. It was found that the threshold increased as the square root of pulse width for pulses longer than several picoseconds. The square root pulselength dependence is expected theoretically for a thermal ablation process and has been found experimentally for various materials at longer pulsewidths. The threshold found in our studies deviates from the traditional thermal ablation dependence on pulsewidth for pulses of duration of several picoseconds and lower. SEM pictures of the ablation craters generated using 100 fs, 1 ps, 5 ps, and 10 ps pulses were examined. It was found that crater morphology changes at pulse widths between 1 ps and 5 ps. Evidence of melting and thermal damage was observed at the walls and edges of the 5 ps and 10 ps craters. A separate experiment, using water, confirmed the transition of ablation characteristics in the range of 1 ps – 5 ps [11]. It was found that a significant amount of energy of 5 ps or longer pulses penetrates through the plasma layer and is volumetrically absorbed along the beam axis. This indicates extensive thermal damage might be introduced into the deeper region by longer pulses. The water experiment was performed during the third year. As a result of these independent studies, it was concluded that 1 ps pulses created ablation characteristics similar to those of 100 fs pulses. This is an important finding since it is likely that the device cost will be much less for manufacturing 1 ps lasers instead of 100 fs lasers. Additionally,1 ps pulses are expected to be deliverable using optical fibers which is not possible for 100 fs pulses due to strong group velocity dispersion and optical fiber damage problems.

Interestingly enough, it was found that larger incident USLP energy does not guarantee faster ablation. We tested the ablation rate with intensities of 2x, 4x, and 7x observed ablation thresholds. The results showed that the ablation rate was approximately 1 μm/pulse for all cases as long as the ablation front moves deeper into the tissues. On the other hand, thermal or mechanical damage was observed at the ablation crater generated using 4x and 7x threshold energies. It appears that the 2x ablation threshold might be an optimal pulse intensity as regards energy efficiency and minimal collateral damage. This result was presented in international conferences and a journal publication is in preparation.

The ablation threshold of USLP was measured as a function of various parameters [12]. It was found that the threshold decreases with high repetition rate, larger beam size, and more pulses, all indicative of importance of thermal processes during ablation. Therefore, high repetition rate USLP ablation may result in some thermal damage if these parameters are not set appropriately. However, it is desirable to have a high repetition rate and large beam size to improve the volume ablation rate. With current commercial USPL systems, the largest pulse output energy is ~1 mJ with a repetition rate of 1 kHz. The maximum beam diameter at which 2x threshold intensity can be reached is thus 280 μm. Therefore, the ablation rate can be up to 0.063 mm^3/sec which means that it takes 16 seconds to ablate 1 mm^3. Increasing the repetition rate to 10 kHz improves the ablation rate to 0.63 mm^3 which is comparable to other tissue removal tools. However, as shown above, higher repetition rate can result in thermal damage. Therefore, it is suggested that a fast beam scanning system might be needed to avoid continuously ablating at a single position and causing thermal damage.

Year 3

During the final year of the project, the focus was on measurement of pressure induced in water by USLP ablation. Purified water was used as a tissue model. A Mach-Zehnder interferometer was devised to directly quantify the density change and thus the pressure of spherical waves generated at the water surface ablation center. The induced pressure was calculated from the phase shift observed in the interferograms [13]. The pressure immediately after the irradiation could not be measured since the phase shift was not obviously discernable. Pressure of spherical shock waves after traveling 50 – 500 μm from the ablation center was measured for the pulse width range of 100 fs - 1 ps. It was found that the pressure is dependent on the multiples of threshold at each pulse width rather than the pulse energy. The pressure decays inversely with distance which is indicative of a weak shock or normal acoustic wave. By integrating pressure over the acoustic waves, the total wave energy was calculated. It was found that the rate of laser energy conversion to pressure was less than 1 % . This finding was confirmed by computer simulation of the USLP-induced pressure waves which also predicted that the energy conversion is lower than 1 %. These pressure studies indicate a much lower energy conversion rate during USLP ablation than that due to long pulsewidth ablation, consistent with the lower observed mechanical damage.

During the three year grant period, we improved our understanding of the USLP ablation process in biological tissues which certainly indicates that USLP technique has potential to be used for high-precision ablation of biomedical materials with low collateral damage. We proposed optimal laser parameters for safe and effective tissue ablation. The USLP market is currently driven by micromachining industries. With recent marked success in USLP technologies, it is expected that compact, affordable USLP ablation systems will be available for medical applications in the near future. A list of potential medical applications that might be benefited by USLP technology was presented in ref. [14]

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